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## SCENARIO DRIVEN EVALUATION AND INTERFERENCE MITIGATION PROPOSALS FOR BLUETOOTH AND HIGH DATA RATE BLUETOOTH ENABLED CONSUMER ELECTRONIC DEVICES

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### ABSTRACT

*Previous research has focussed on residential coverage and achievable data rates using the Bluetooth Personal Area Network (PAN) standard. To meet the bit rate needs of future consumer electronics devices, this led to the proposed use of M-PSK modulation schemes as likely candidates for high data rate extensions to Bluetooth. This paper investigates the effects of interference occurring between high data rate time-bounded and non-time bounded Bluetooth enabled consumer electronic devices. Frequency hopping selection kernels for both the 79-hop and the 23-hop systems in Bluetooth were implemented in software. Using this model, collision statistics were obtained between a wanted Bluetooth user (in a piconet) and interferers (other Bluetooth users in different piconets) operating under typical scenarios that were constructed within the test environment. These scenarios featured piconets operating in an office environment in both synchronous and asynchronous modes as well as with typical up and downlink loading factors. A detailed link level physical layer simulation was used to obtain packet error rate performance based on the collision statistics obtained. Finally, a state-of-the-art indoor space-time propagation modelling tool was used to analyse the data throughput performance capabilities for Bluetooth data medium (DM) and data high (DH) rate packets. Results highlight a clear need to mitigate interference by employing synchronous communication in future Bluetooth evolution networks.*

### I. INTRODUCTION

Bluetooth is a point-to-point universal radio interface for ubiquitous connectivity in the area of Personal Area Networks (PAN). The technology currently operates in the unlicensed 2.45GHz ISM band and utilises frequency hopping with terminals cycling through 79 1MHz hop channels (or 23 1MHz hop channels in Japan, France and Spain) at 1600 hops/s [1]. One of the drawbacks with the current standard is its restricted bit-rate of 1Mb/s. Although this may seem adequate for low bit rate applications such as data modems, cordless telephones and low bit rate videophones, it is insufficient to support high bit rate VCR/TV quality digital video (2-12Mb/s).

Previous research [2] has shown that high data rates can be achieved by employing coherent M-PSK modulation schemes in future Bluetooth evolutions instead of the current GFSK scheme.

Although the findings show great scope for future high data rate Bluetooth enabled consumer electronic devices, the data throughput performance of these devices may still be limited due to the interference present in the 2.45GHz band. The coexistence between various wireless local area network (LAN) standards, such as those based on the IEEE 802.11b and Home RF, pose a huge problem. The majority of research interest has so far focussed on the impact of Bluetooth on Wireless LANs and vice-versa [3-8]. However, given the impending avalanche of Bluetooth enabled consumer electronic devices in the market, there is great concern voiced over the interference between Bluetooth enabled devices themselves.

The fundamental issue with Bluetooth piconets operating within the same environment is that they are not time synchronised to each other and thus, a collision will occur in both time and frequency. As a result, data transmissions on unwanted piconets can interfere with the data transmissions on a wanted piconet. Consequently, the requirement to retransmit packets will increase, thus reducing the overall data throughput. The frequency collisions will obviously depend on the proximity of piconets within the environment and the transmit power levels (1mW for ranges up to 10m and 100mW for ranges up to 100m). This paper investigates a scenario driven environment which allows a realistic projection of the behaviour of Bluetooth piconets.

Section II outlines the Bluetooth frequency hopping kernel implemented in software. This is shown in Figure 1. In Section III, the Bluetooth communication structure is explained. In Section IV, software simulated frequency collision statistics for both synchronous and asynchronous cases are presented. Section V outlines the development of an indoor propagation modelling tool and presents the resulting data throughput graphs. Section VI summarises the results and discusses vital points for proposals that will help to mitigate interference between high data rate Bluetooth enable devices.

## II. BLUETOOTH FREQUENCY HOPPING KERNEL

Two frequency-hopping model kernels were implemented following the 79-hop and 23-hop Bluetooth pattern used in the connection state [9]. The kernel structure is shown in Figure 1 and signals A to F, X, Y1 and Y2 are defined in Table 1. The choice of frequencies consists of two parts, i.e. selecting a sequence (indicated by the white boxes) and mapping this to the hop sequence (indicated by the shaded grey box). In the 79-hop Bluetooth pattern, the selection scheme chooses a segment of 32 hops spanning over 64MHz. Likewise, in the 23-hop Bluetooth pattern, the selection scheme chooses a segment of 16 hops spanning over 23MHz. Once a segment of hops is chosen, the hop frequencies are visited once in a random order. In both cases, a different segment of hops is chosen everytime.

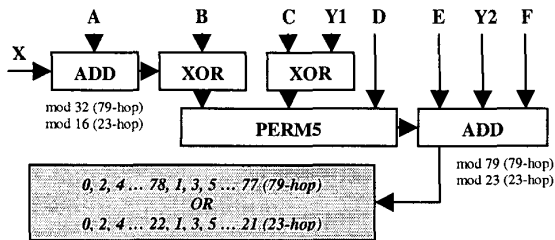


Figure 1: Block diagram showing the hop selection kernel for the 79-hop and 23-hop system

Input Signal	Connection State (79-hop system)	No. of Bits	Connection State (23-hop system)	No. of Bits
X	CLK <sub>6,2</sub>	5	CLK <sub>5,2</sub>	4
Y1	CLK <sub>1</sub>	1	CLK <sub>1</sub>	1
Y2	32 x CLK <sub>1</sub>	1	16 x CLK <sub>1</sub>	1
A	BD_ADDR <sub>27-23</sub> XOR CLK <sub>25-21</sub>	5	BD_ADDR <sub>27-23</sub> XOR CLK <sub>25-21</sub>	5
B	BD_ADDR <sub>22-19</sub>	4	BD_ADDR <sub>22-19</sub>	4
C	BD_ADDR <sub>8,6,4,2,0</sub> XOR CLK <sub>20-16</sub>	5	BD_ADDR <sub>8,6,4,2,0</sub> XOR CLK <sub>20-16</sub>	5
D	BD_ADDR <sub>18-10</sub> XOR CLK <sub>15-7</sub>	9	BD_ADDR <sub>18-10</sub> XOR CLK <sub>15-7</sub>	9
E	BD_ADDR <sub>13,11,9,7,5,3,1</sub>	7	BD_ADDR <sub>13,11,9,7,5,3,1</sub>	7
F	16 x CLK <sub>27-7</sub> mod 79	7	8 x CLK <sub>27-6</sub> mod 23	5

Table 1: Device addresses and clock information of the master used for input into the frequency hop kernel

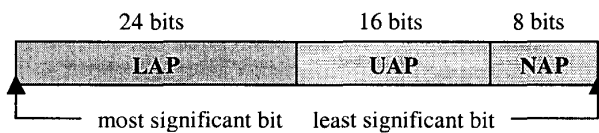


Figure 2: Structure of the Bluetooth device address

In Bluetooth, each transceiver is allocated a unique 48-bit Bluetooth device address (BD\_ADDR). The BD\_ADDR is

divided into 3 fields as shown in Figure 2. In the connection state, the BD\_ADDR of the master (24 bits of the lower address part, LAP and the 4 least significant bits of the upper address part, UAP) as well as the master clock's (CLK) 27 most significant bits, MSB is used in the hop selection kernel.

The first addition operation adds a constant to the phase and applies a modulo 32 or a modulo 16 operation. The 4 least significant bits of this output is XOR-ed with signal B, whereas the most significant bit is carried through unchanged. In the 23-hop sequence, the most significant bit is ignored. The permutation or switching operation consists of 7 stages of butterfly operations that are implemented with multiplexers. The butterfly operations can be visualised as a wave matrix where the output of the first stage influences the subsequent stage and so on until the final stage is reached. Each stage of the butterfly operation consists of two control signals, resulting in a total of 14 control signals (5 provided by the XOR operation between signals C and Y1 and 9 provided by signal D). The output from the first XOR operation is used to trigger the first stage of the butterfly operation.

The second addition operation only adds a constant to the output of the permutation and applies a modulo 79 or a modulo 23 operation. This ensures that the 16-hop or 32-hop segment chosen is mapped differently on the hop frequencies. The output of the addition addresses a register bank containing synthesiser code words corresponding to either 79 or 23 hop frequencies. The upper half of the register bank stores the even hop frequencies and the lower half stores the odd hop frequencies. This ensures that each 32-hop segment spans over 80% of the available 79MHz band and the 16-hop segment spans over the entire 23MHz band. As a result, the desired frequency spreading over a short time interval is attained.

## III. BLUETOOTH COMMUNICATION STRUCTURE

The Bluetooth communication structure is based on an ad-hoc network. A group of Bluetooth units sharing the same channel is known as a piconet. Each piconet contains a master and up to seven active slaves. All Bluetooth units within a piconet hop using the same hop pattern defined by the BD\_ADDR and CLK of the master. Since each piconet contains a master with a unique BD\_ADDR and a different CLK, the hop pattern varies from one piconet to another.

In the current Bluetooth system, a slotted channel is used for transmission with each slot spanning 625μs. User data is transmitted through packets – nominally covering a single time slot, but can be extended to up to five time slots. In single time slot packet transmission, the duty cycle is 366μs. The rest of the time (259μs) is used for

transient time-settling. In three and five time slot packet transmissions, the duty cycle is  $1.616\mu\text{s}$  and  $2.866\mu\text{s}$  respectively. For full duplex transmission, a Time Division Duplex (TDD) scheme is used. Each single time slot packet is transmitted on a different hop frequency whereas a single hop frequency is used for the entire span of a multi time slot packet. The hop frequency in the first time slot after a multi time slot packet shall use the frequency as determined by the current Bluetooth clock value.

In Bluetooth, six symmetric asynchronous data link (ACL) packets are defined. These include three medium data rate packets (DM 1, 3 and 5) and three high data rate packets (DH 1, 3 and 5). Section V explains more about the ACL packet types used in this investigation (DM1 and DH5).

Although piconets in the current Bluetooth standard are not synchronised, this study investigates both synchronous and asynchronous cases. Synchronous transmission as implied here means that all the piconets are time synchronised with each other. The investigation begins by calculating the number of frequency collisions that occur in the downlink direction between a single wanted piconet and up to 4 unwanted piconets/interferers when they are in the connection state (i.e. during user data transmission). In this study, downlink is defined as transmission from *master to slave* and uplink is defined as transmission from *slave to master*. Downlink transmissions occupy even numbered time slots whereas uplink transmissions occupy odd numbered time slots.

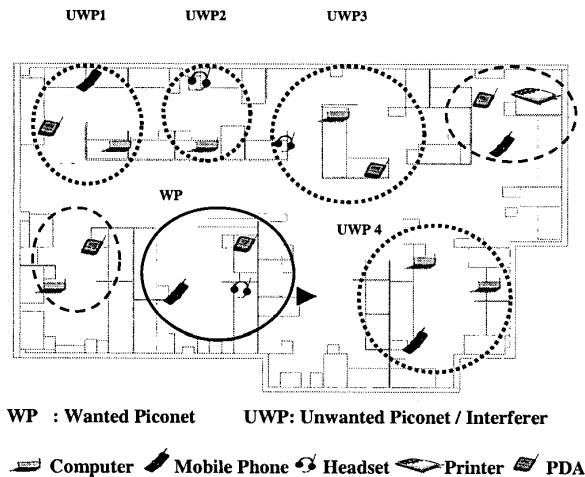


Figure 3: Plan view of a typical office environment (18.5m by 13.8m) containing 5 piconets with distributed Bluetooth enabled consumer electronic devices

Figure 3 shows the test environment containing 5 piconets (1 wanted piconet and 4 interferers). In the synchronous case, the downlink hop frequency of the wanted piconet at time slot  $N$  is compared to the downlink hop frequency of

the interferer at time slot  $N$ . In the asynchronous case however, the downlink hop frequency of the wanted piconet at time slot  $N$  is compared to the downlink and uplink hop frequencies of each interferer at time slot  $N$  and  $N-1$  respectively. If the hop frequency is the same when compared, this indicates that a collision has occurred at that particular instant. This was performed over an average of 1000 hop patterns for every piconet, each derived from a different BD\_ADDR and CLK. Each hop pattern spans 10000 time slots.

Piconet	Master (TX)	Slave (RX)	Distance (TX <sub>UWP</sub> -RX <sub>WP</sub> )	Distance (RX <sub>UWP</sub> -RX <sub>WP</sub> )
WP	Mobile Phone	PDA	-	-
UWP1	PDA	Computer	8.64 m	6.17 m
UWP2	Headset	Computer	6.15 m	5.34 m
UWP3	Computer	PDA	7.30 m	4.40 m
UWP4	Mobile Phone	Computer	5.32 m	6.36 m

Table 2: Transmitter and receiver in each piconet and their relative distance from the receiver of the wanted piconet

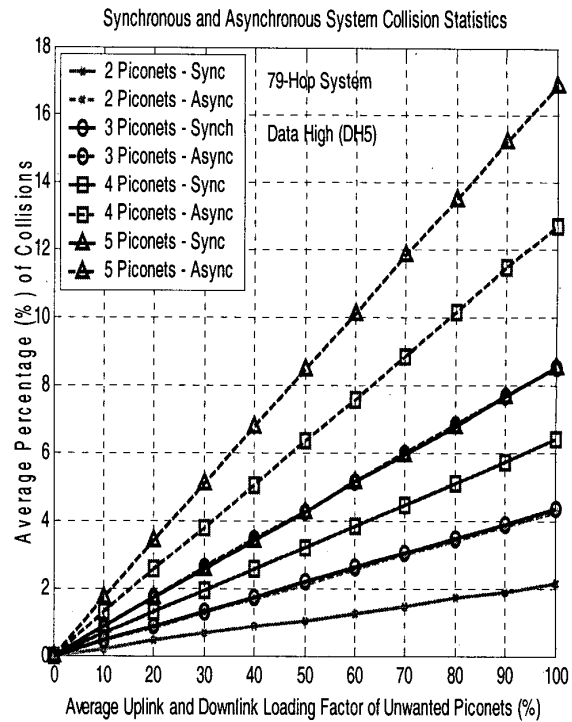
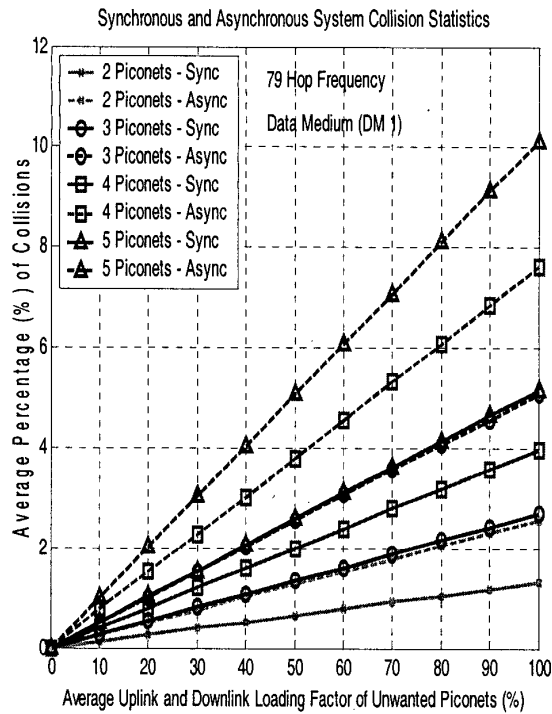
Table 2 lists the devices selected for transmission in each piconet and their relative distance from the receiver of the wanted piconet. The software simulation was carried out assuming a worse case scenario. Hence, the following points were observed:

- The uplink and downlink loading factors were assumed to be 100% for the wanted piconet.
- The average uplink and downlink loading factors for each interfering piconet was varied from 0%-100% in steps of 10%.
- For DH5 packets, the downlink transmission occupied 5 time slots and the uplink transmission occupied 1 time slot.

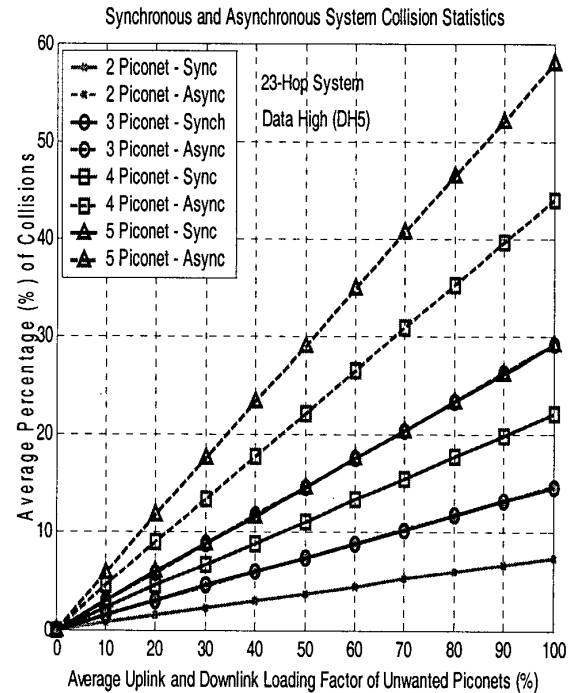
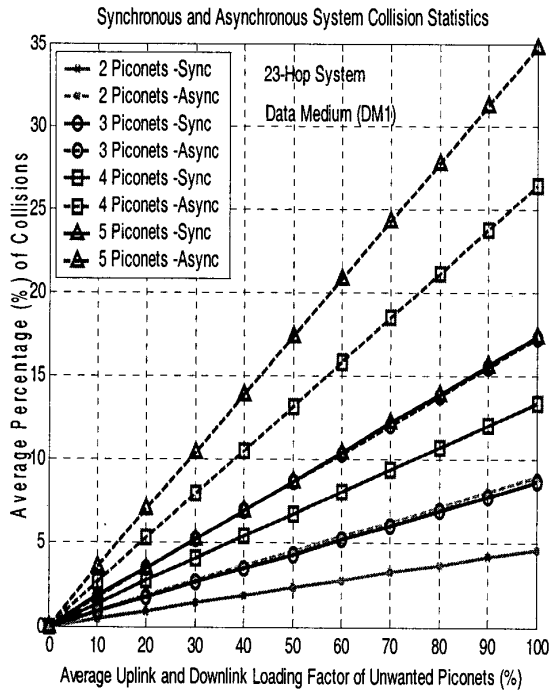
#### IV. SOFTWARE SIMULATED FREQUENCY COLLISION STATISTICS

Although the investigation focussed on downlink collision statistics on the wanted piconet, from preliminary investigations there is clearly no distinction to be made between uplink and downlink collision statistics assuming the loading factors for the wanted and interfering piconets are identical to that above and also the uplink transmission occupies 5 time slots in the DH5 packet. Multiple counting was an issue in this model. Hence, if a multiple collision occurred, this was accounted for as 1 collision to ensure a more accurate study. As a result, the total number of downlink frequency collisions was distributed evenly across every interfering piconet.

Figures 4(a)-(d) show the number of downlink frequency collisions in synchronous and asynchronous systems for both 79 and 23-hop systems using DM1 and DH5 packets.



Figures 4(a) and (b): Frequency collision statistics for 79-hop system in synchronous and asynchronous cases using DM1 and DH5



Figures 4(c) and (d): Frequency collision statistics for 23-hop system in synchronous and asynchronous cases using DM1 and DH5

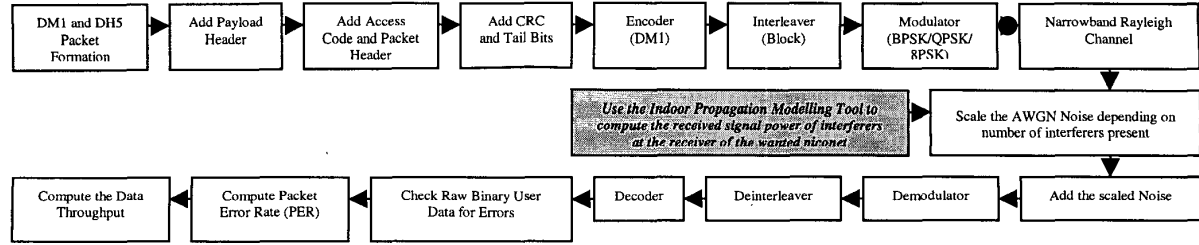


Figure 5: Block diagram showing the Bluetooth modem implemented in software

Packet Type	No. of UWP	79-Hop System		23-Hop System	
		Sync (%)	Async (%)	Sync (%)	Async (%)
DM1	1	1.3	2.6	4.5	8.9
	2	2.7	5.3	8.6	17.2
	3	4.0	7.8	13.3	26.5
	4	5.1	10.1	17.4	34.7
DH5	1	2.1	4.2	7.2	14.5
	2	4.3	8.5	14.5	29.0
	3	6.4	12.7	22.0	44.0
	4	8.5	16.8	29.0	58.0

Table 3: Summary of downlink frequency collision statistics at 100% average uplink and downlink loading factors

Table 3 records results when the uplink and downlink loading factors of the interfering piconets is 100%. Immediate observations confirm that the number of frequency collisions is reduced by 50% in synchronous systems. In the 23-hop system, the frequency collisions are approximately 3.43 times greater than that for the 79-hop system. This is because only 23 out of the 79 hop channels are available. The collision statistics are very similar for 2 interferers (Sync) and 1 interferer (Async) as well as for 4 interferers (Sync) and 2 interferers (Async). This is due to the fact that in asynchronous systems, the wanted piconets downlink hop frequencies are compared with both the uplink and downlink hop frequencies of the interfering piconets. Statistically this yields the same results in the synchronous case for twice the number of interferers. The slight discrepancies in the graphs are due to the simulation being performed over limited number of realisations. Thus, assuming the average uplink and downlink loading factors are the same in both cases, synchronous collision statistics in the presence of  $Y$  interferers can be predicted using the information obtained from the asynchronous collision statistics in the presence of  $Y/2$  interferers and vice versa.

## V. BLUETOOTH MODEM, INDOOR PROPAGATION MODEL AND DATA THROUGHPUT

Frequency collision statistics obtained from the aforementioned investigation were used to analyse the average data throughput that can be achieved within the test environment. The first stage of developing this

involved simulating a standard Bluetooth modem in software. This is shown in Figure 5.

The packet header for all ACL packets in Bluetooth is protected by a simple  $1/3^{\text{rd}}$  rate repetition code and decoded using a maximal polling method. The payload header and payload of all medium data (DM) rate packets are protected by an additional forward error correcting mechanism (a  $2/3^{\text{rd}}$  rate shortened (15, 10) Hamming binary block code). Decoding at the receiver is performed using the single error correcting decoding algorithm using a predefined parity check matrix [10]. The payload header and payload of all high data high (DH) rate packets are not protected by any forward error correcting mechanism in order to optimise the data throughput.

Three PSK modulation schemes, BPSK, QPSK and 8-PSK were implemented, thus producing a maximum data rate of 1, 2 and 3Mb/s respectively. Coherent detection at the receiver was used as opposed to differential detection. Although this type of detection is far more complex and involves expensive radio design (requiring automatic gain and phase control in addition to linear up and down conversion and power amplification) in practise, the advantages of being able to exploit greater bandwidth efficiency and improved radio sensitivity make this form of detection a more attractive option.

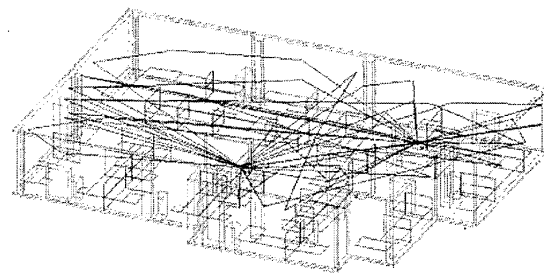


Figure 6: Ray geometry plot for the test indoor environment

A state-of-the-art indoor space-time propagation model [11] based on ray launching [12-14] is used to predict the complex temporal and spatial characteristics of the radio channel for the test environment concerned. Figure (6)

Packet Type	Mode	$E_b/N_0$ (dB)	Data Throughput (kb/s)											
			BPSK				QPSK				8-PSK			
			79-hop		23-hop		79-hop		23-hop		79-hop		23-hop	
			1 UWP	4 UWP	1 UWP	4 UWP	1 UWP	4 UWP	1 UWP	4 UWP	1 UWP	4 UWP	1 UWP	4 UWP
DM1	Synch	15	100	97	96	83	200	190	193	166	275	268	266	230
		30	108	105	106	91	214	205	208	180	320	308	310	268
	Async	15	98	92	93	66	196	182	188	131	273	248	253	180
		30	103	99	103	75	213	198	206	150	318	292	304	210
	No Interferer	15	102				202				279			
		30	108				217				325			
DH5	Synch	15	570	540	580	430	1130	1050	1080	820	1300	1200	1220	940
		30	700	660	670	520	1410	1320	1340	1040	2090	1960	1990	1520
	Async	15	560	500	510	240	1110	970	1000	490	1260	1110	1130	550
		30	670	600	635	330	1380	1210	1230	650	2050	1780	1840	960
	No Interferer	15	594				1155				1320			
		30	718				1435				2130			

Table 5: Data throughputs for various  $E_b/N_0$  values for DM1 and DH5 packets in synchronous and asynchronous modes

shows a ray geometry plot for the indoor test environment studied. The received signal power of the interferers at the receiver of the wanted piconet was generated for a maximum of 6 orders of reflections and transmissions combined with a single order of diffraction. Short dipole antennas were used at each transceiver, located 0.8m above the floor (typical desk height).

The test environment is primarily a software research office with partitioned workspaces containing mainly blocks with a plaster layer. It has a suspended floor that is made of high-density floorboards with an upper metal sheet. Such an environment is commonplace in UK office environments. The relative permittivity and conductivity of the material are 6 and 0.05S/m respectively. The maximum transmit and receive gains of the antennas is 2.0dBi [15]. A peak transmit power of 0dBm (1mW) is assumed.

The model was used to calculate the received signal power at the receiver of the wanted piconet due to transmissions from interfering piconets. When a collision occurs, the received signal power from interfering piconets is assumed to be an AWGN noise source in this investigation. As a result, the transmitted packet in the wanted piconet is susceptible to a higher degree of noise (rise in the noise floor) and hence increases the chances of it becoming corrupted. Packet Error Rate (PER) versus the ratio of energy per bit to noise power spectral density ( $E_b/N_0$ ) plots were obtained. These results were used to compute the data throughput (DT) curves using the following relationship:

$$DT = (1 - PER) \times \log_2 M \times DR$$

where  $M$  is the constellation size (2 for BPSK, 4 for QPSK and 8 for 8-PSK) and  $DR$  is the data rate for DM1 and DH5 (as specified in the Bluetooth standard). Hence, the

maximum symmetric data rates for the DM1 and asymmetric data rate for the DH5 packets using different modulation schemes are listed in Table 4.

ACL Packet	Maximum Data Throughput (kb/s)		
	BPSK	QPSK	8-PSK
DM1	108.8	217.6	326.4
DH5	723.2	1446.4	2169.6

Table 4: Maximum data throughputs for DM1 and DH5 packets

Figures 7(a)-(d) show the average data throughput curves for medium and high data rate packets for synchronous and asynchronous transmissions. The plots display results for both 79 and 23 hop-systems. The data throughput curve specifies the maximum data rate achievable at the receiver of the wanted piconet in the presence of 1-4 interferers in the test environment using BPSK, QPSK and 8-PSK modulation schemes.

## VI. RESULTS AND DISCUSSION

Table 5 summarises the maximum achievable data rates in the presence of 1 and 4 unwanted piconets (UWP)/interferers as well as when no interferers are present. These results have been summarised for two  $E_b/N_0$  values; 15dB when the performance is noise limited and 30dB when the performance is interference limited. The results are compared to the data rates achievable when no interferers are present. For example, at 15dB using DH5 packet in asynchronous transmission with BPSK, the data throughput is 500kb/s and 240kb/s rather than the maximum achievable 718kb/s and 594kb/s for the 79-hop and 23-hop systems respectively. From observations, it can be seen that at low  $E_b/N_0$  values, the data throughput achieved using DM1 packet is not severely affected for the 79 and 23-hop systems for the synchronous and asynchronous cases in the presence of low number of

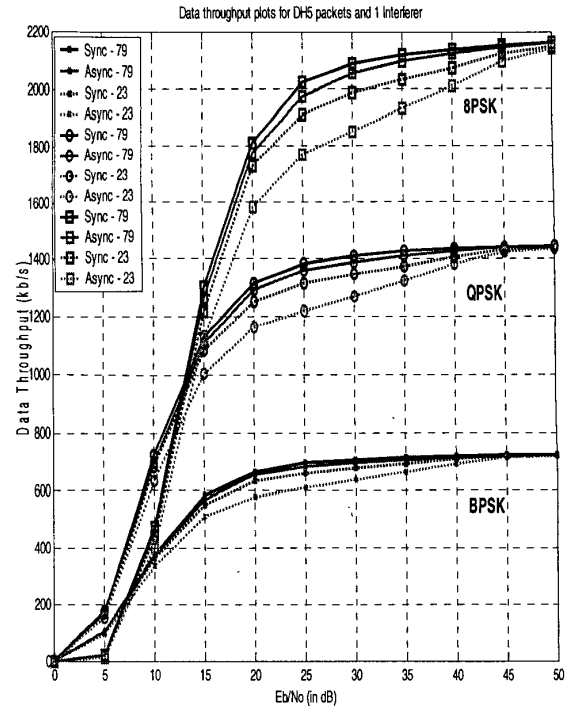
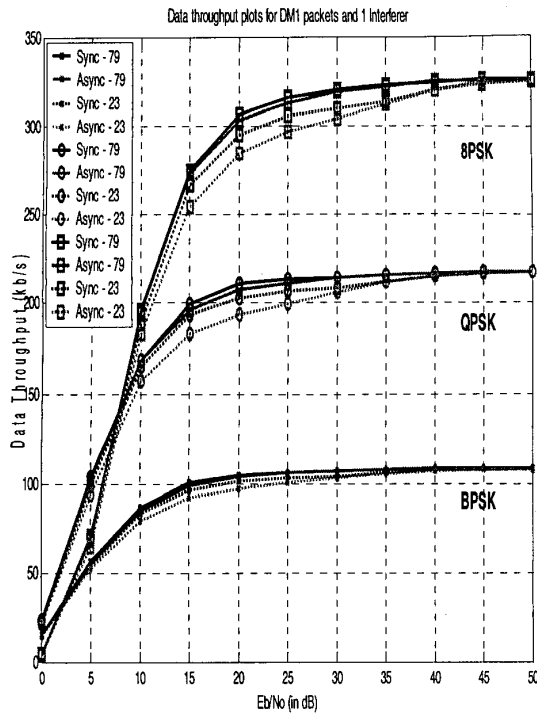


Figure 7(a) and (b): Data throughput plots for DM1 and DH5 packets respectively in the presence of 1 interferer

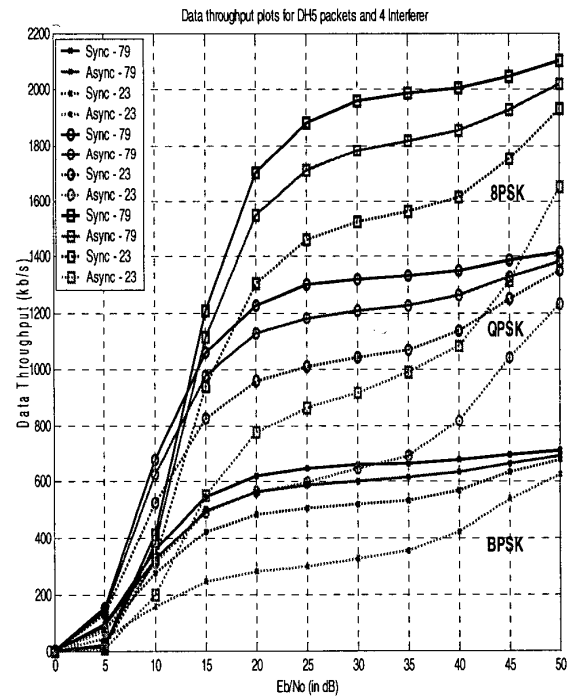
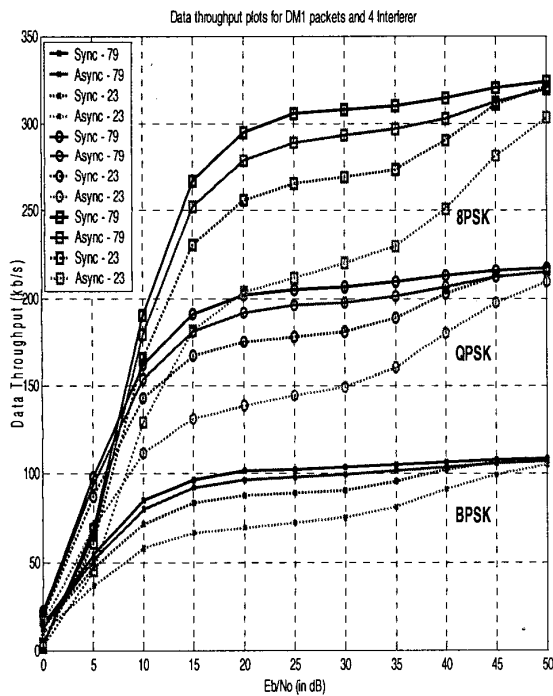


Figure 7(c) and (d): Data throughput plots for DM1 and DH5 packets respectively in the presence of 4 interferers



interferers. However in the presence of high number of interferers, the impact is greater especially for the 23-hop system. This can be explained by the fact that in the 79-hop system, the percentage of achievable data rates is higher since greater bandwidth is available for transmission.

Packet Type	Average percentage of improvement attained in data throughput by employing synchronous transmission instead of asynchronous transmission (%)					
	BPSK		QPSK		8-PSK	
	79-hop	23-hop	79-hop	23-hop	79-hop	23-hop
DM1 1UWP	2.50	3.14	1.58	2.53	1.00	3.19
DM1 4UWP	5.35	16.09	3.96	15.85	5.59	17.74
DH5 1UWP	2.51	8.28	1.74	7.11	2.45	7.34
DH5 4UWP	8.03	29.62	7.37	28.21	8.09	28.25

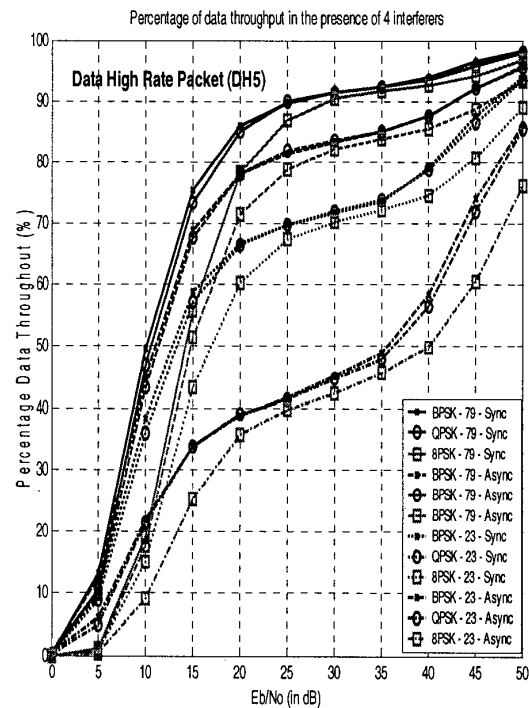
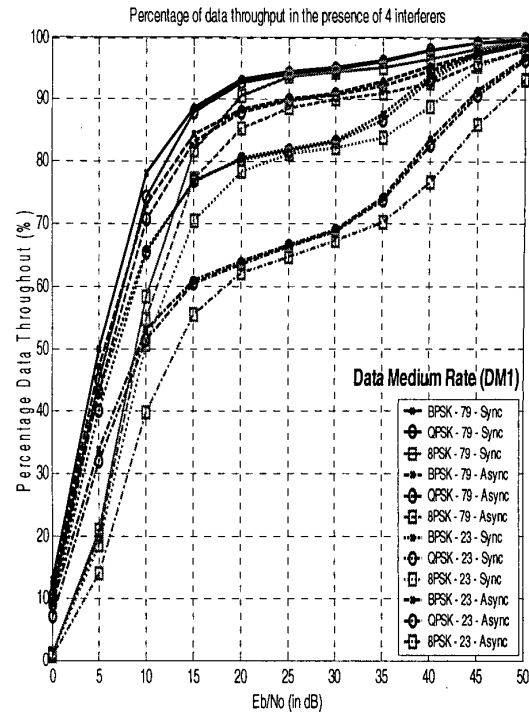
[WP: Wanted Piconet UWP: Unwanted Piconet]

Table 6: Average percentage improvement in data throughput achieved when synchronous system is employed in the presence of 1 and 4 interferers in the environment

Table 6 shows the average percentage improvement in data throughput when the transmission scheme changes from asynchronous to synchronous. These figures were obtained from Table 5 where the average increase in performance was calculated over the specified  $E_b/N_0$  values. It can be seen that in the presence of 1 interferer, employing synchronous transmission in the 79-hop system only improves the performance marginally (between 1% and 2.52%) for both types of packets. However, these figures increase to between 2.53% and 8.28% in the 23-hop system for both types of packets. In the presence of 4 interferers, the improvement in data throughput performance for both types of packets is only between 4% and 8.4% for the 79-hop system and between 15% and 30% for the 23-hop system.

These results show that the degradation is more significant for multi-slot packet transmission in Bluetooth. This is expected since the entire packet spanning 3 or 5 time slots will be retransmitted if it is corrupted. As a result, the data throughput of the system is reduced. The degradation is far more severe for the 23-hop system and as such by deploying synchronous transmission, a significant improvement in performance is obtained. This is especially prominent when a large number of interferers are present.

Figures 8(a) and (b) show the percentage data rate achievable in the presence of 4 interferers in the environment. The plots were obtained by using the data throughput results shown in Figures 7(c) and (d) and comparing it relative to the maximum achievable data rate for each packet type and for each modulation scheme. The percentage of data throughput achievable reduces with higher level modulation schemes. This is because for



Figures 8(a) and (b): Percentage data throughput achievable for DM1 and DH5 packets respectively for 79 and 23-hop systems

higher level modulation schemes, the number of bits per symbol increases. This effectively means that the symbols are closer together on a constellation diagram (i.e. the Euclidean distance is reduced for a given average energy per symbol). Consequently, the symbols are more prone to noise thus resulting in a higher number of corrupted symbols. This in turn reduces the maximum data throughput achievable. From Figures 8(a) and (b), it can be seen that in the 23-hop system, only 68% and 45% data throughput is achievable at an  $E_b/N_0$  value of 30dB for DM1 and DH5 packets respectively using asynchronous transmission. However, this increases to 83% and 72% respectively if synchronous transmission is employed. Likewise, in the 79-hop system, at an  $E_b/N_0$  value of 30dB, 90% and 83% data throughput is achievable for DM1 and DH5 packets respectively using asynchronous transmission. These figures increase to 95% and 91% when synchronous transmission is used. In the presence of more interferers, these figures will decrease thus limiting the system performance.

## VII. CONCLUSIONS AND FUTURE WORK

The frequency collision statistics indicate that the performance degradation obtained in Bluetooth is linearly dependent on the available bandwidth. From the results and data analysis presented, it can be concluded that although the collision statistics may seem high, the impact it has on the data throughput is not as catastrophic as expected. This can be used to predict the performance of high data rate time-bounded and non-time bounded Bluetooth enabled consumer electronic devices in a typical office environment. In real time applications packet reliability is important since packet retransmissions are not practical. Hence it is vital that the data throughput is at an acceptable level such that the quality of performance is not degraded.

It can be seen that although asynchronous transmission may not have a serious impact on the data throughput for the 79-hop system, in the presence of a large number of interferers, the performance is unreliable for time-bounded Bluetooth enabled applications. In the 23-hop system, the use of asynchronous transmission is certainly not favourable altogether for time-bounded high quality cordless digital applications such as digital video and TV. In such scenarios, synchronous transmission using DH5 packets are strongly recommended. In addition, increasing the operating bandwidth by a factor of 2-4 times will enable optimum usable TV/VCR data rates to be achieved in practice.

The performance of non-time bounded Bluetooth enabled consumer electronic applications are promising even in the presence of large number of interferers for both the 79-hop and 23-hop sequence. A vast majority of non-time bounded

applications such as good quality audio streaming over the internet as well as web browsing, cordless telephones (DECT), videophones, modems and personal digital assistants (PDAs) are therefore feasible in practise. Although this is still also possible in asynchronous systems, the trade-off between quality and performance is far more attractive in synchronous transmission.

The results suggest that high data rate Bluetooth enabled applications are good in handling self interference. These encouraging results however do not apply when high data rate Bluetooth enabled devices are working in the presence of other consumer electronics devices using various wireless LAN standards such as those based on the IEEE 802.11b and Home RF standard. This is because of the fast frequency hopping scheme in Bluetooth which hops over the entire allocated bandwidth over which it operates. One possible way of improving the performance in these types of scenarios would be to employ some form of 'intelligent' hopping mechanism which will enable both types of devices to coexist in harmony within the same environment.

The effects of frequency collisions depend largely on the proximity of piconets within the environment as well as the transmit power levels. Although the transmit power level in this investigation was limited to 1mW (0dBm), in practise this can be increased up to 100mW in order to achieve greater data throughput and also for transmission ranges greater than 10m. However, the disadvantage of doing this is that neighbouring Bluetooth piconets or other wireless LAN products transmitting at lower power levels will be interfered by high powered transmissions operating within the environment. In addition, the location of piconets within the environment is a crucial factor since interferers lying in line of sight to the wanted piconet will have a greater impact than those lying in non-line of sight positions.

Given the use of ray-tracing, the results obtained are specific and depends on the geometry of the office environment considered. The thickness of the walls and ceilings as well as the material used to construct the indoor environment influences the performance of both synchronous and asynchronous systems.

From this investigation, it has been highlighted that synchronous transmission in high data rate Bluetooth enabled consumer electronic devices offer a more favourable system performance compared to the currently employed asynchronous transmission. Clearly in order for this to be possible, a suitable means for channel access and channel control is needed. Although this mode of operation does not completely combat interference present in the environment, it certainly helps to mitigate the effects of interference while maintaining reasonable data throughput

performances especially for good quality time-bounded applications. Fundamentally, since the available bandwidth is limited, it appears that higher bit rates are more readily achieved by increasing the operating bandwidth beyond 1MHz.

Future work involves employing synchronous transmission in high data rate Bluetooth systems and investigating the improvement in performance when suitable spatial and temporal interference mitigating techniques are applied. Synchronous transmission in Bluetooth is an attractive option since it enables space-time block codes to be deployed to suppress interferers. This technique does not require any explicit knowledge about the interferer and thus it does not require any channel estimation of the interferer [16]. The second technique for interference mitigation is the classical null-steering technique which trains the antennas using the LMS algorithm [17-18].

### ACKNOWLEDGEMENTS

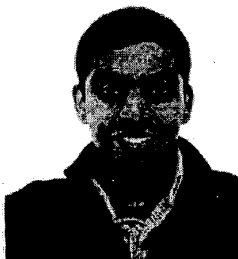
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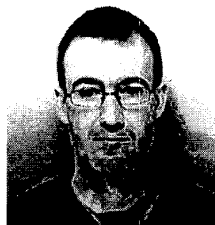
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